NOVEL, MULTIDISCIPLINARY GLOBAL OPTIMIZATION UNDER UNCERTAINTY

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NASA LEARN Project Final Briefing
01/15/2015

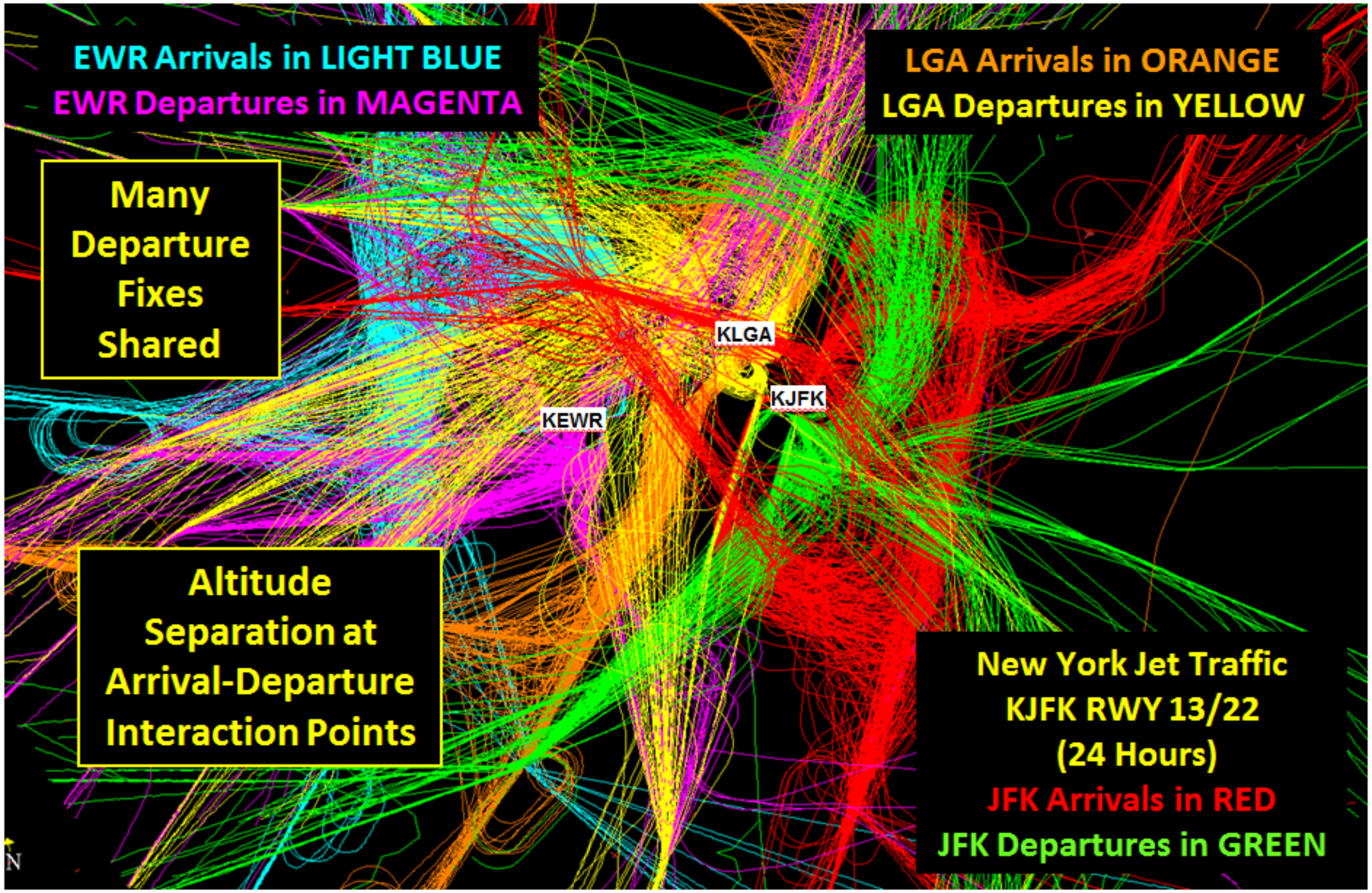
PRESENTATION OUTLINE

- Introduction: The Metroplex Problem and Its Challenges
- Overview of the Project: Our Solution for Addressing the Challenges
- Project Technical Approach
- Results to Date
- Significance of Our Innovation
- Next Steps: Plans for Phase II Research Work

THE METROPLEX PROBLEM

- Two or more busy airports in close proximity
- Shared entry/exit points to the terminal airspace
- Inter-dependent, crossing arrival and departure flows
- Several traffic control facilities involved

The New York Metroplex



Ref: Geogia Tech, Saab Sensis Corp., ATAC Corp., Metron Aviation, "Final Briefing for NASA NRA Characterization of and Concepts for Metroplex Operations," at NASA Langley Research Center, Nov. 2009

SIGNIFICANCE TO THE NATIONAL AIRSPACE SYSTEM

- FAA's Future Airport Capacity Task team report[(1)]
  - Eight metropolitan areas would require additional capacity by 2025, even after taking FAA's planned improvements into consideration

- RTCA NextGen Mid-Term Implementation Task Force 5[(2)]
  - *"Relieve congestion and tarmac delays at major metropolitan airports, inefficiencies at satellite airports, and surrounding airspace"*

- Key Aeronautics Challenges (National Aeronautics R&D Plan[(3)])
  - Increasing airport approach, surface and departure capacity, and
  - Developing capability to perform four-dimensional trajectory (4DT)-based planning

(1) FAA, "Capacity Needs in the National Airspace System, 2007-2025: An Analysis of Airports and Metropolitan Area Demand and Operational Capacity in the Future," FAA Future Airport Capacity Task (FACT) team report, May 2007.
(2) RTCA, "NextGen Mid-Term Implementation Task Force Report," September 9, 2009.
(3) National Science and Technology Council, "National Aeronautics Research and Development Plan," February 2010.

THE CHALLENGES TO AN OPTIMIZED, DE-CONFLICTED 4DT SOLUTION

- Complex interactions and network impacts
  - Requires integrated planning across airport surface and terminal airspace
- Uncertain future traffic behavior
  - Requires planning under the possibility of multiple different futures
- Competing and nonlinear objectives
  - Requires optimization-algorithms capable of handling complex objective functions

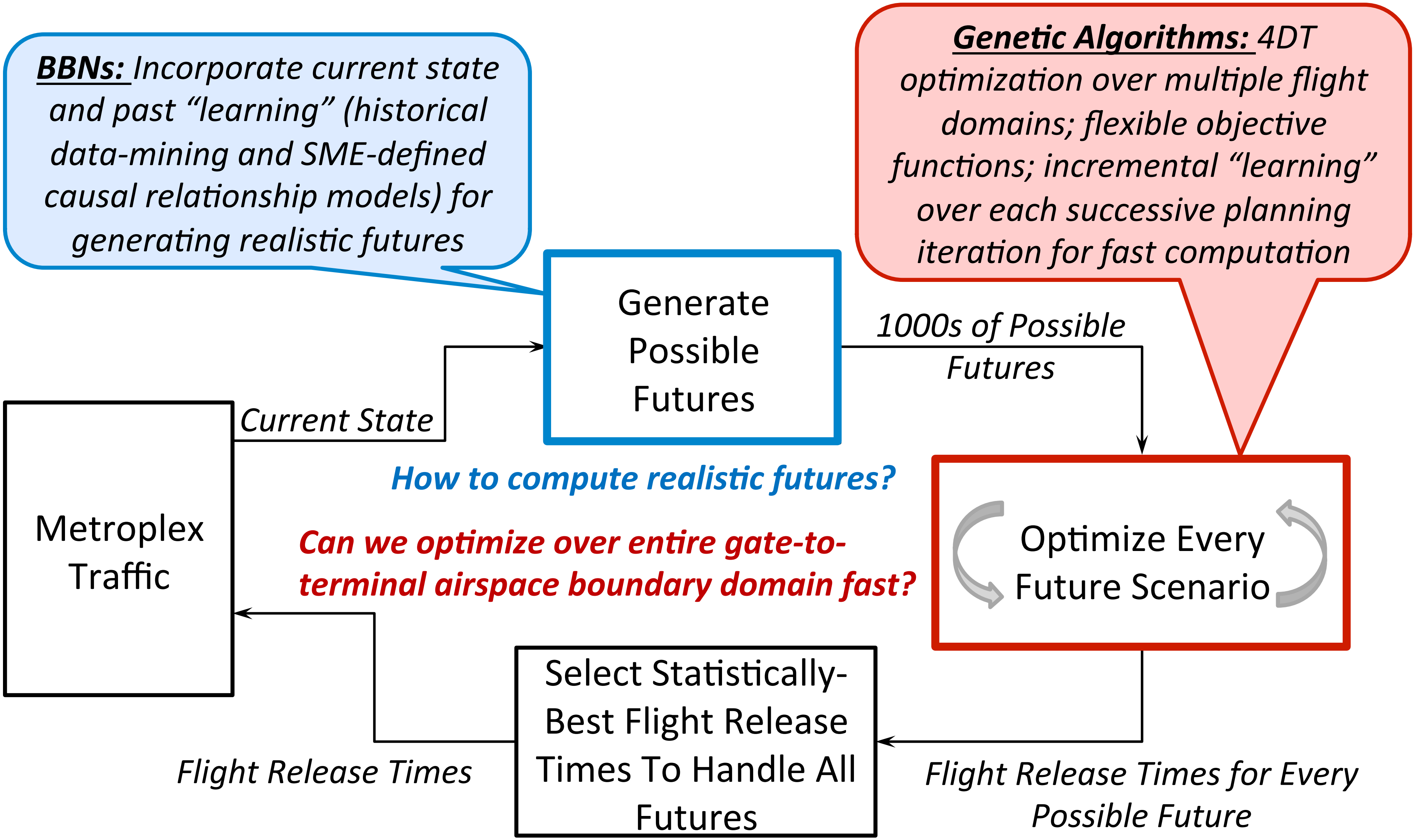
OUR LEARN PROJECT—OVERVIEW

Objectives:

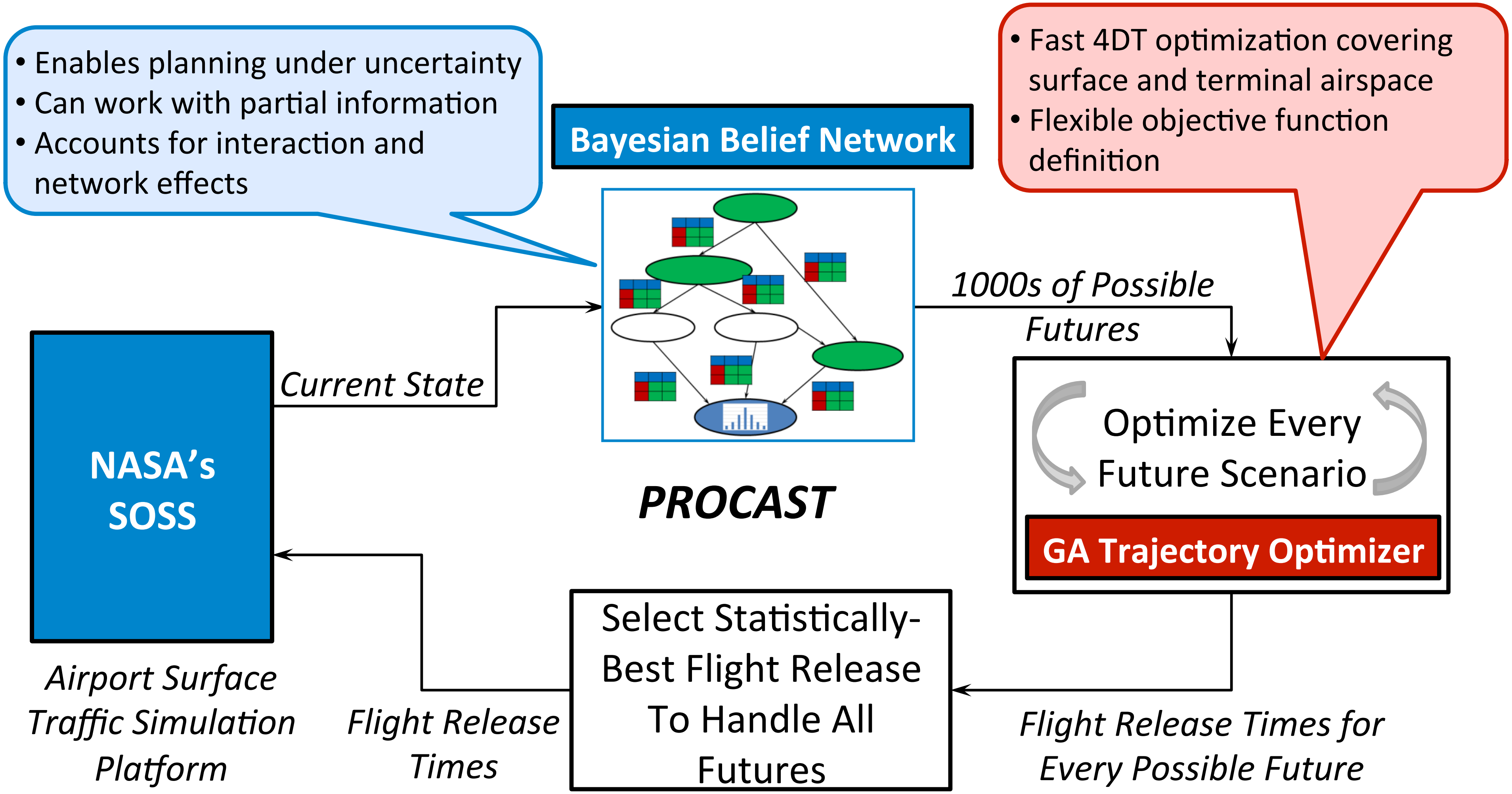
- Develop 4DT-based traffic management tool called ***PROCAST*** by combining cutting-edge technologies from two diverse fields
  - Predictive technology/Data Science: Bayesian Belief Networks (BBNs)
  - Optimization technology: NGA's Continuous Re-planning Engine (NACRE)
- Perform proof-of-concept demonstration by conducting simulation experiments using a test problem—New York metroplex traffic scheduling
  - In Phase I, we focus on a single-airport, arrival-departure-surface scheduling problem
  - Selected John F. Kennedy International Airport (JFK) as the focus site
- Enhance NASA simulation platform to enable terminal airspace traffic simulation and pre-pushback process modeling

PROCAST—Probabilistic Robust Optimization of Complex Aeronautics Systems Technology

WHAT IS THE INNOVATION?



PHASE I TECHNICAL APPROACH



PROCAST ELEMENTS

- Bayesian Belief Networks
  - Estimating pushback readiness times and transit times on airport surface
- NACRE Genetic Algorithm for optimizing 4D trajectories
- SOSS simulation platform enhancements
  - Added modeling of terminal airspace traffic
  - Added pre-pushback process uncertainty models
- Simulation-based benefits assessment of PROCAST
  - Modeled current-day operations at JFK as a comparison baseline
  - Compared simulation performance using realistic traffic scenarios
- Concept of operations for PROCAST DST

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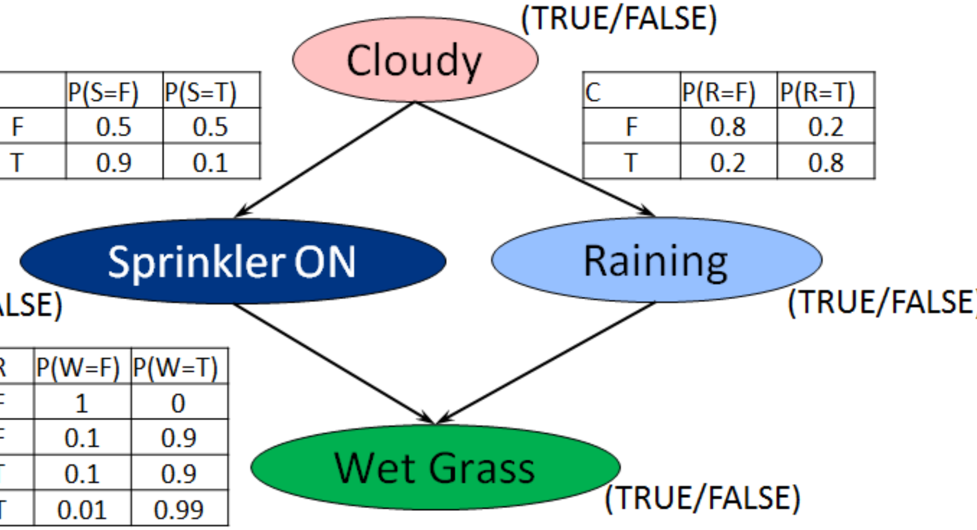
WHAT ARE BAYESIAN BELIEF NETWORKS (BBNs)?

- BBN is a directed, acyclic graph
  - Nodes: Variables of interest
  - Arcs: Statistical or causal dependencies
- BBNs decompose complex joint probability distributions into smaller factors using ***conditional independence***
- Subject matter experts design the graph structure using insights about the processes

<u>*A Simple BBN Example*</u>



C	P(S=F)	P(S=T)
F	0.5	0.5
T	0.9	0.1

C	P(R=F)	P(R=T)
F	0.8	0.2
T	0.2	0.8

S R	P(W=F)	P(W=T)
F F	1	0
T F	0.1	0.9
F T	0.1	0.9
T T	0.01	0.99

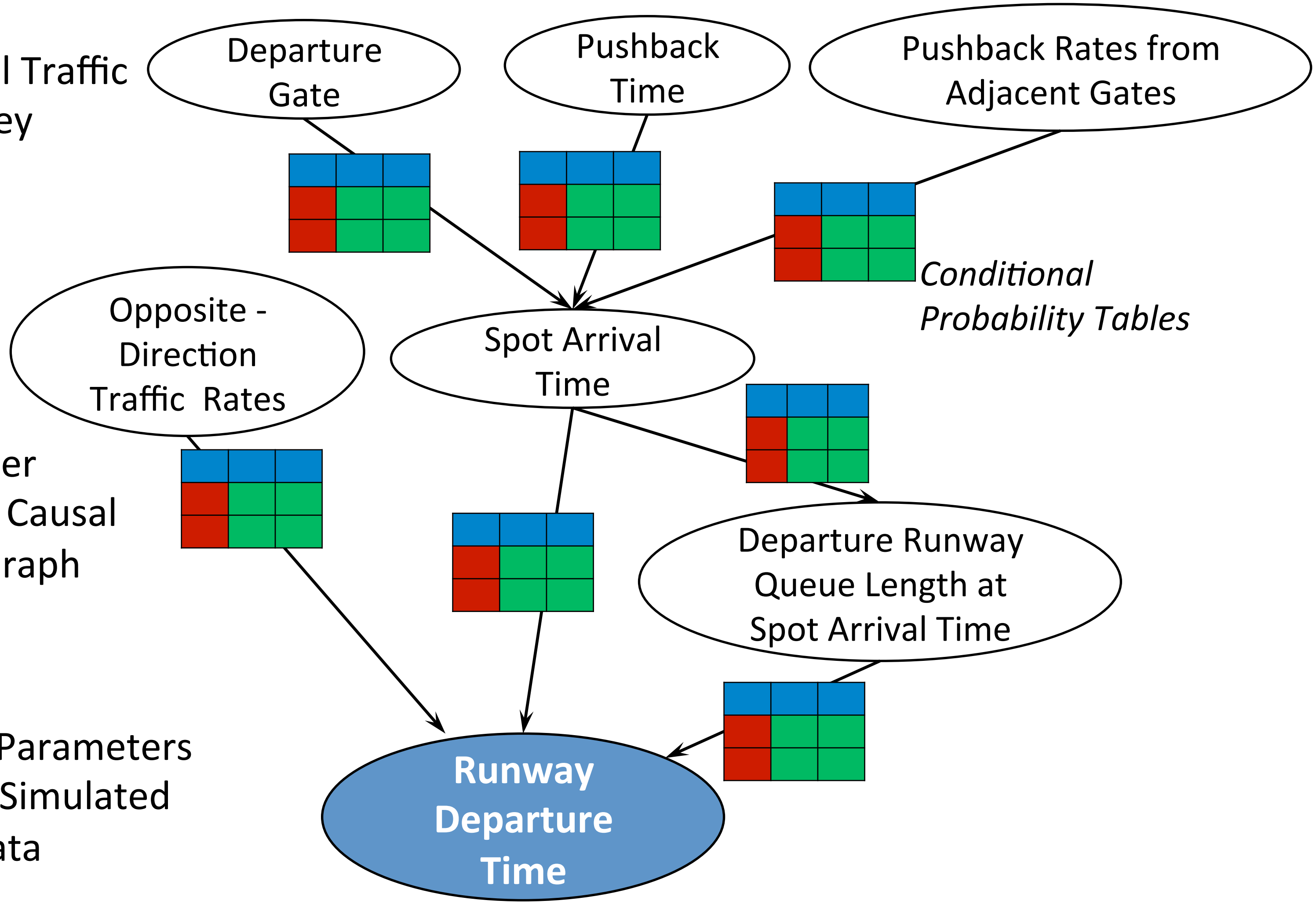
- Machine learning is used to “learn” the parameters
- BBNs provide fast inference for
  - Prediction (from causes to effects)
  - Diagnosis (from effects to causes)
  - Explaining away (tie-break between two or more causes)

BBN FOR PREDICTING THE TIME DIMENSION

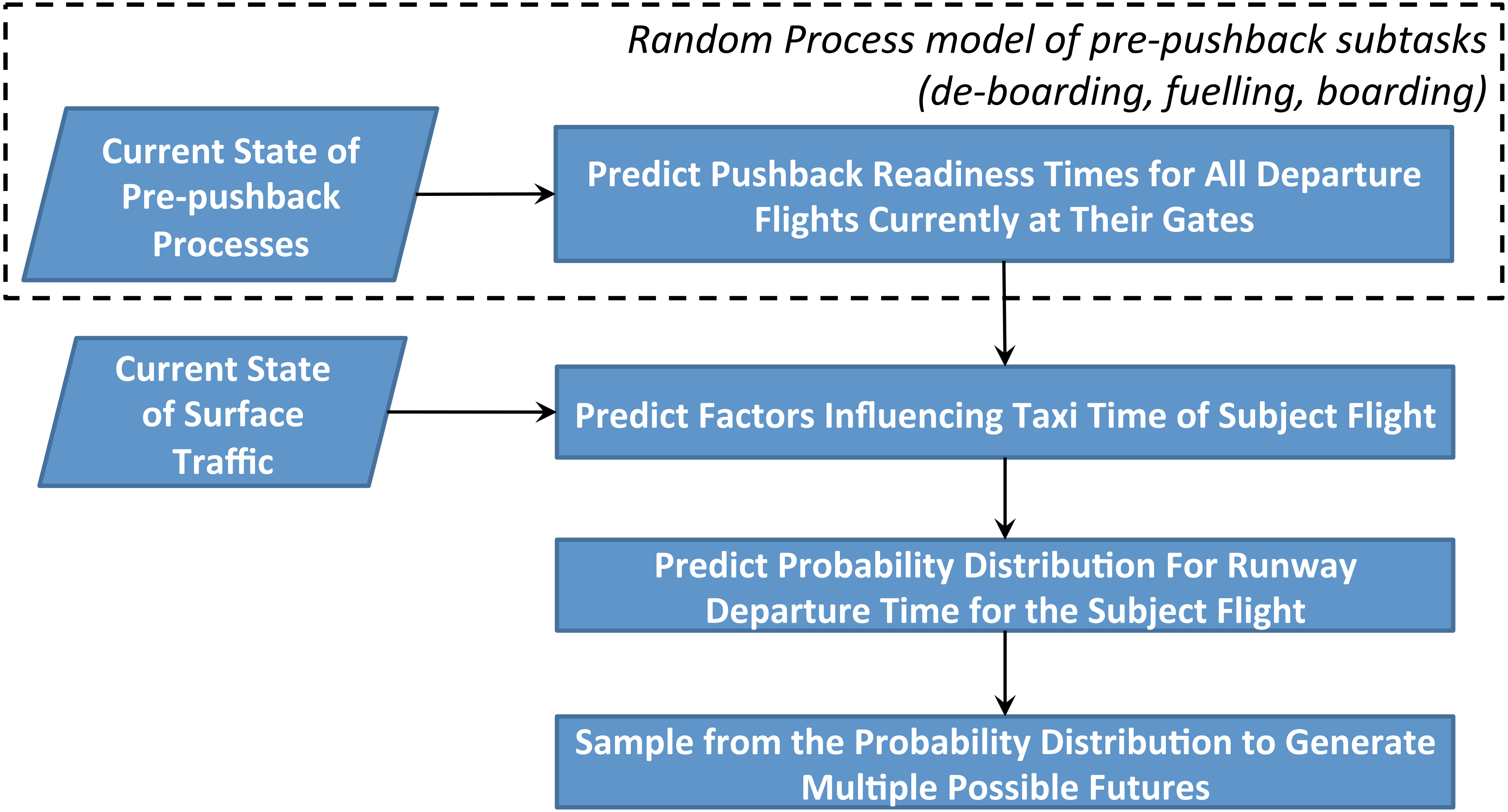
1. Analyze Historical Traffic Data and Identify Key Influencing Factors

2. Use Subject Matter Expertise To Model Causal Relationships in a Graph

3. Train the Graph Parameters Using Recorded or Simulated Historical Traffic Data



GENERATING REALISTIC FUTURE SCENARIOS USING BBNs



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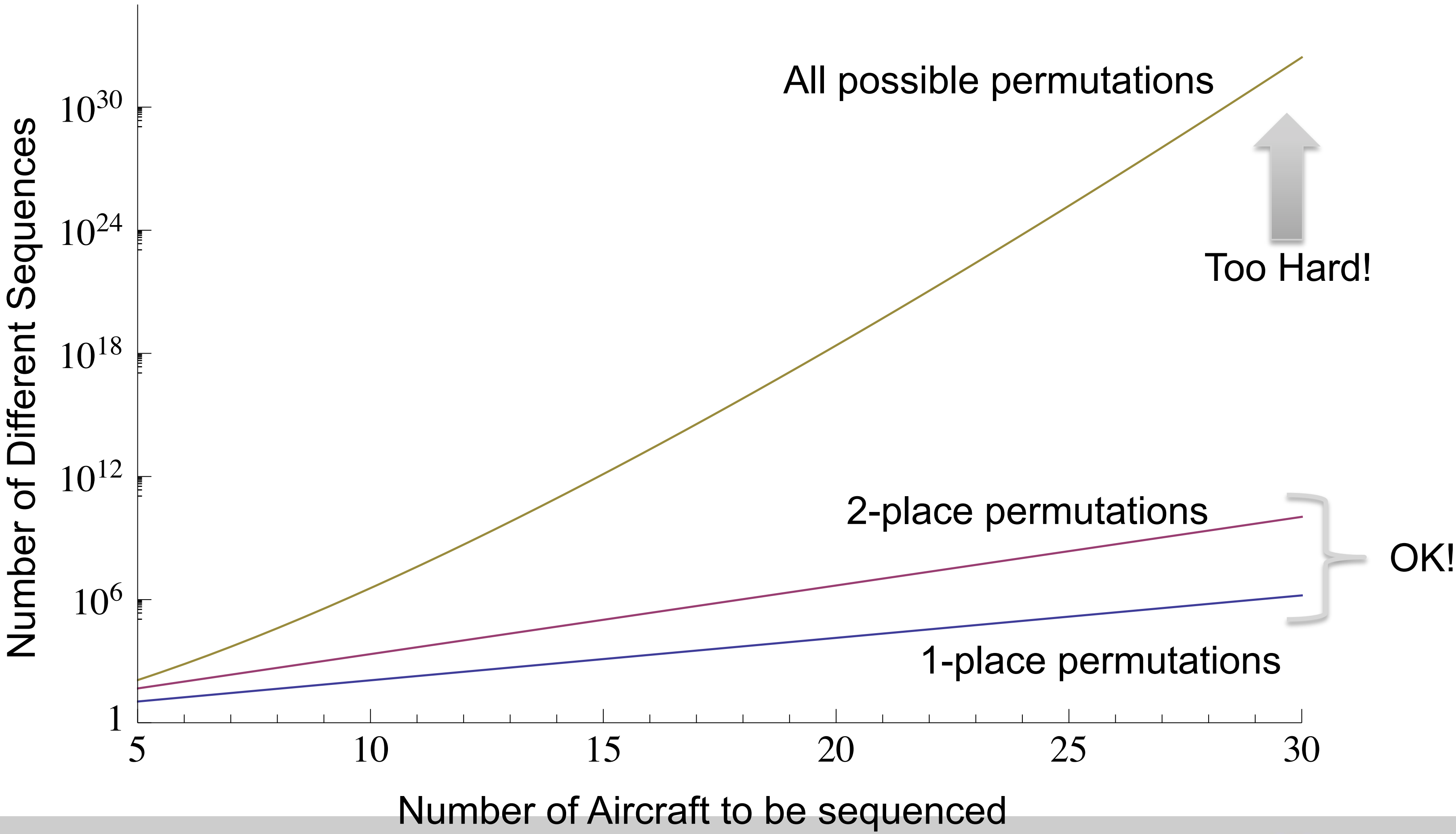
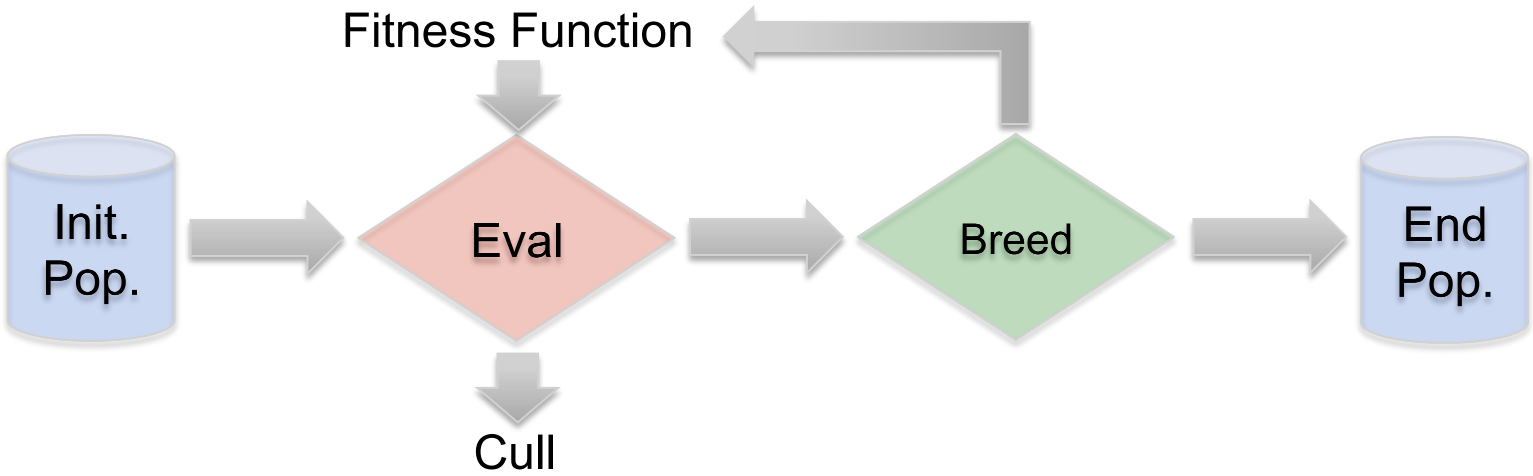
THE PROBLEM ADDRESSED BY NACRE

- The most valuable resource of an airport are its runways
- To sequence runways, consider
  - Wake vortex separation (weight class of aircraft)
  - Interleaving of arrivals
  - Departure fix
  - Frequent updates to arrival/departure information (PROCAST)
- How NACRE works
  - First optimize runway usage (arrivals and departures)
  - Then organize surface traffic planning around runway usage
  - Avoid using tarmac for aircraft storage

SEARCH SPACE SIZE-RUNWAY SEQUENCING



GENETIC ALGORITHM FOR SEQUENCING



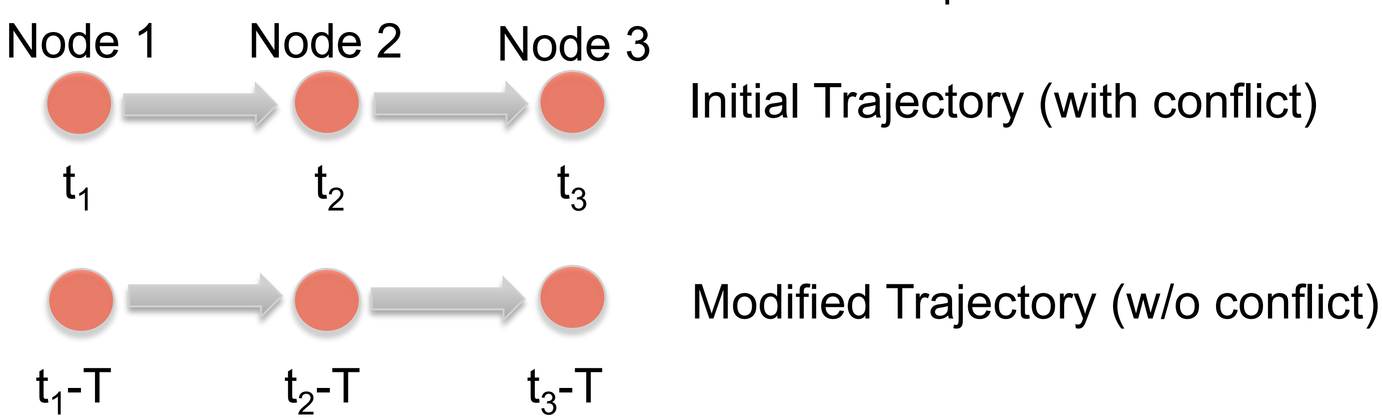
- NACRE GA encodes runway sequencing
- Position shifts encoded as elements in a genome
- Quality of solutions evaluated
  - By throughput
  - By sum of squares of delays (to prevent any one aircraft from getting all the pain) A genetic algorithm (GA) encodes partial solutions, like a genome
  - GAs work well when partial solutions are well – correlated to complete solutions. In the runway sequencing problem, reorderings in different parts of the sequence contribute mostly additively to fitness.

HOW MANY SMALL SEARCHES COVER LARGE SPACES

Original sequence	a	b	c	d	e	f	g	h
One permutation away	b	a	c	d	e	g	f	h
One permutation away	b	c	a	d	g	e	f	h
One permutation away	c	b	d	a	g	f	e	h
Net movement	2	0	1	3	2	0	2	0

AN INNOVATIVE APPROACH TO OPTIMIZING SURFACE MOVEMENTS

- Surface dynamics driven ultimately by optimized runway schedule
- Start with runway schedule, calculate taxi dynamics backwards in time to meet schedule
- Deconflict by “rigid time translation”
  - Leave gate earlier by time T sufficient for deconfliction
  - Wait at runway queue for the same time T
  - Runway queue acts as shock absorber
  - Minimize number of aircraft in motion on airport surface



NACRE SEQUENCER/OPTIMIZER SUMMARY OF FUTURE DIRECTIONS

- Optimize on additional criteria:
  - Economically (based on A/C cost model, number of pax, etc.)
  - Airline Network integration (priority of flight depends on context, such as having to meet connecting flights or not)
  - History of delays (spread delays around fairly by airline, aircraft, etc.
- Use “hot start” capability of GA for bigger/harder problems
  - For sufficiently rapid replanning cycles, much of old solution is still valid
  - GAs strong point is incorporation of “partial solutions”
- Scale the GA to bigger/harder problems
  - Preserve speed so as to keep using BBN capability in real-time
  - Parallelizable on inexpensive hardware (GPU card, for instance)
  - Metroplex ground/TRACON problem

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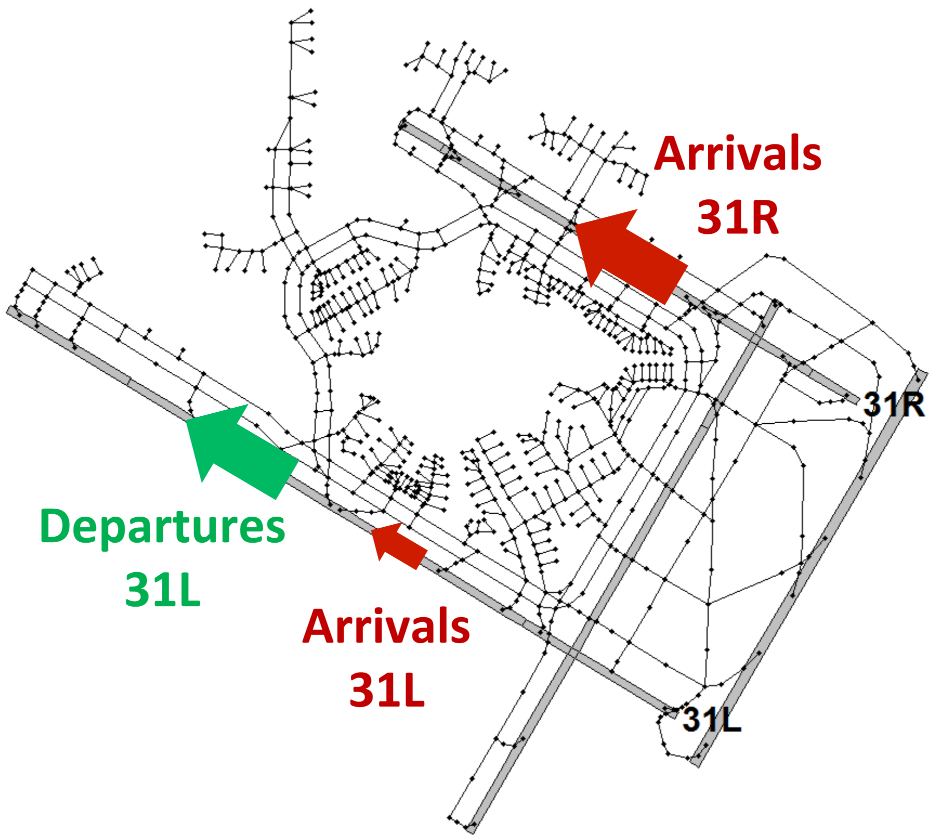
SIMULATION-BASED BENEFITS ASSESSMENT
SIMULATION TRAFFIC SCENARIO

- Selected one of the most commonly used runway configurations for simulation
- Derived realistic traffic scenarios from recorded surface surveillance (ASDE-X) data and airline schedules (OAG)
- Selected three 2-hour busy-traffic time-periods from 2013 for simulation
  - Scenario #1: November 24, 2013; 7 to 9 PM Local time; 82 departures, 63 arrivals
- Simulation Parameters
  - Planning Horizon: 45 minutes
  - Planning Frequency: Once every 5 minutes



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SIMULATION-BASED BENEFITS ASSESSMENT

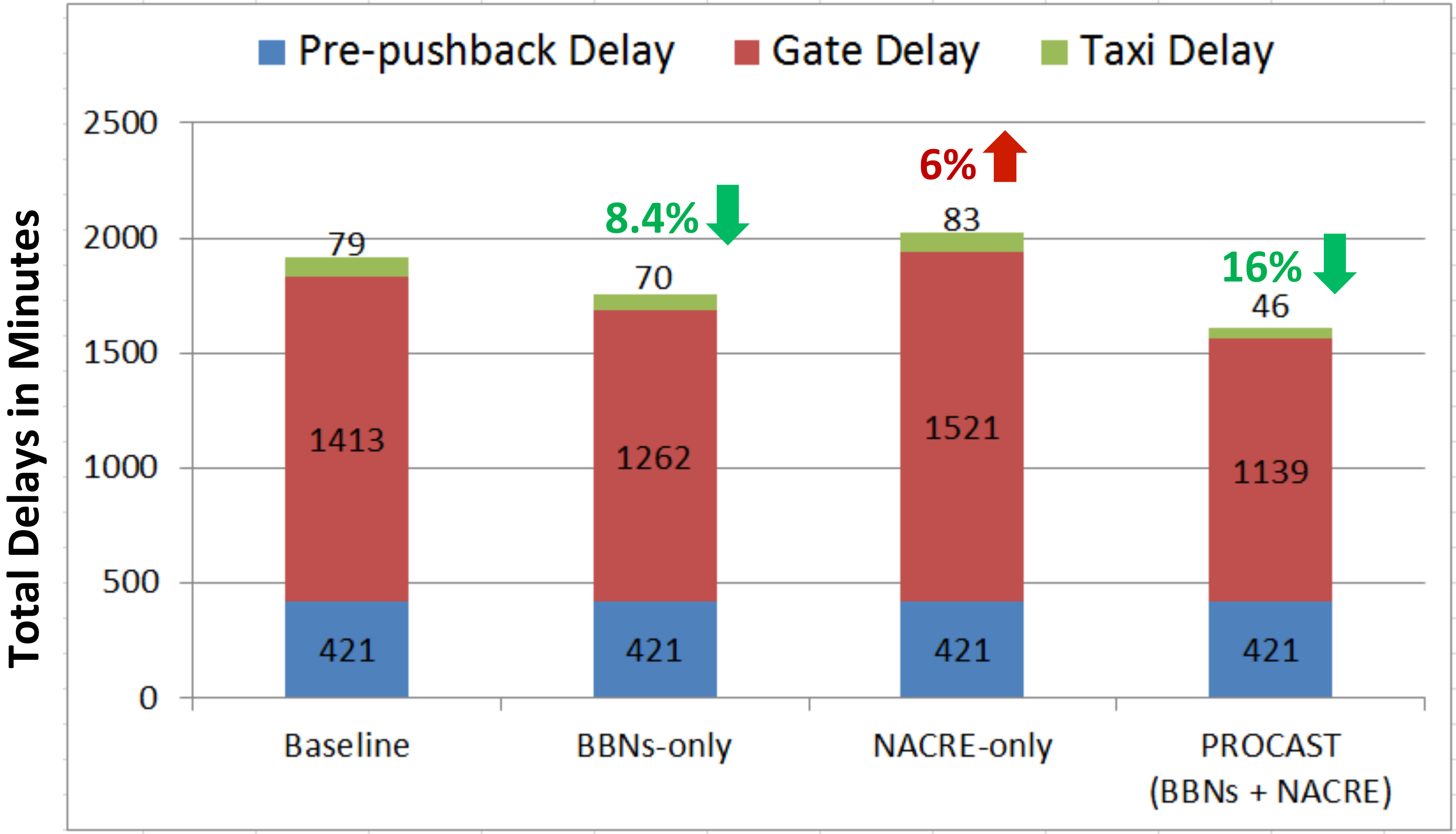
- Compared simulated JFK surface and terminal operations as controlled by PROCAST against simulated current-day baseline operations

<table>
<tr><th></th><th>Baseline Operations</th><th>PROCAST Operations</th></tr>
<tr><td>Scheduling method for Departures</td><td>• Simple, deterministic departures-only planning similar to current-day Departure Management Tools
• Uses nominal pushback readiness time estimates</td><td rowspan="2">• Combined arrival-departure planning
• Assumes periodic updates of pre-pushback process state
• BBNs generate multiple futures
    • Including estimates of pushback readiness times and times of arrival at key nodes in the surface-terminal network
• GA optimizes arrival and departure operations over each future
• Statistical assessment selects best flight release times</td></tr>
<tr><td>Scheduling method for Arrivals</td><td>Deterministic arrivals-only planning based on current-day Traffic Management Advisor (TMA) scheduling algorithms</td></tr>
</table>

TWO OTHER VARIANTS OF PROCAST

	BBNs-only Operations	NACRE-only Operations
Scheduling method for ***Departures***	• Assumes periodic updates of pre-pushback process state • BBNs generate multiple futures • Departures-only planning similar to baseline for each future scenario • Statistical assessment selects best flight release times	• Combined arrival-departure planning • Only one future scenario is generated using nominal estimates of pushback readiness times, as in baseline operations • GA optimizes arrival and departure operations over only one future scenario
Scheduling method for ***Arrivals***	Arrivals-only planning similar to baseline for each future scenario	

DELAY DISTRIBUTION FOR DEPARTURES



November 24, 2013, 7-9 PM Local Time Traffic Scenario (82 Departures)

DEPARTURE BENEFITS OVER MULTIPLE TRAFFIC SCENARIOS

Traffic Scenario	BBNs-only Savings	NACRE-only Savings	PROCAST Savings
November 24, 7-9 PM *(82 departures, 63 arrivals)*	+ 8%	- 6%	+16%
November 27, 8-10 PM *(72 departures, 60 arrivals)*	+ 12%	+ 0.2%	+24%
October 27, 11 AM-1 PM *(62 departures, 90 arrivals)*	+ 8%	+ 5%	+17%

PROCAST ESTIMATED ANNUAL SAVINGS

- Assuming similar conditions prevail for 100 days per year:

Quantity	Savings
Gate Delay	2,400 hours
Total Delay in Metroplex	3,000 hours
Fuel	155,000 gallons
Fuel Cost	$ 322,000
Operating Costs	$ 5 million
CO_2 Emissions	9.8 metric tons
Passenger Time	14,000 person-days
Passenger Time @ $30/hr	$ 10 million
Passenger Time NAS-wide	$ 15 million

Assumptions:
Fuel burn rate = 8 kg / min taxiing, 40 kg / min airborne, cost = $ 993.60 / metric ton
Operating costs = $ 27 / min at gate, $ 41 / min taxiing, $ 78 / min airborne
*1 minute savings in NYC = 1.5 minute savings NAS-wide**

*Stroiney S., Levy B., Khadikar H., Balakrishnan H., "Assessing the Impacts of JFK Ground Management Program," DASC, Syracuse, NY, 2013.

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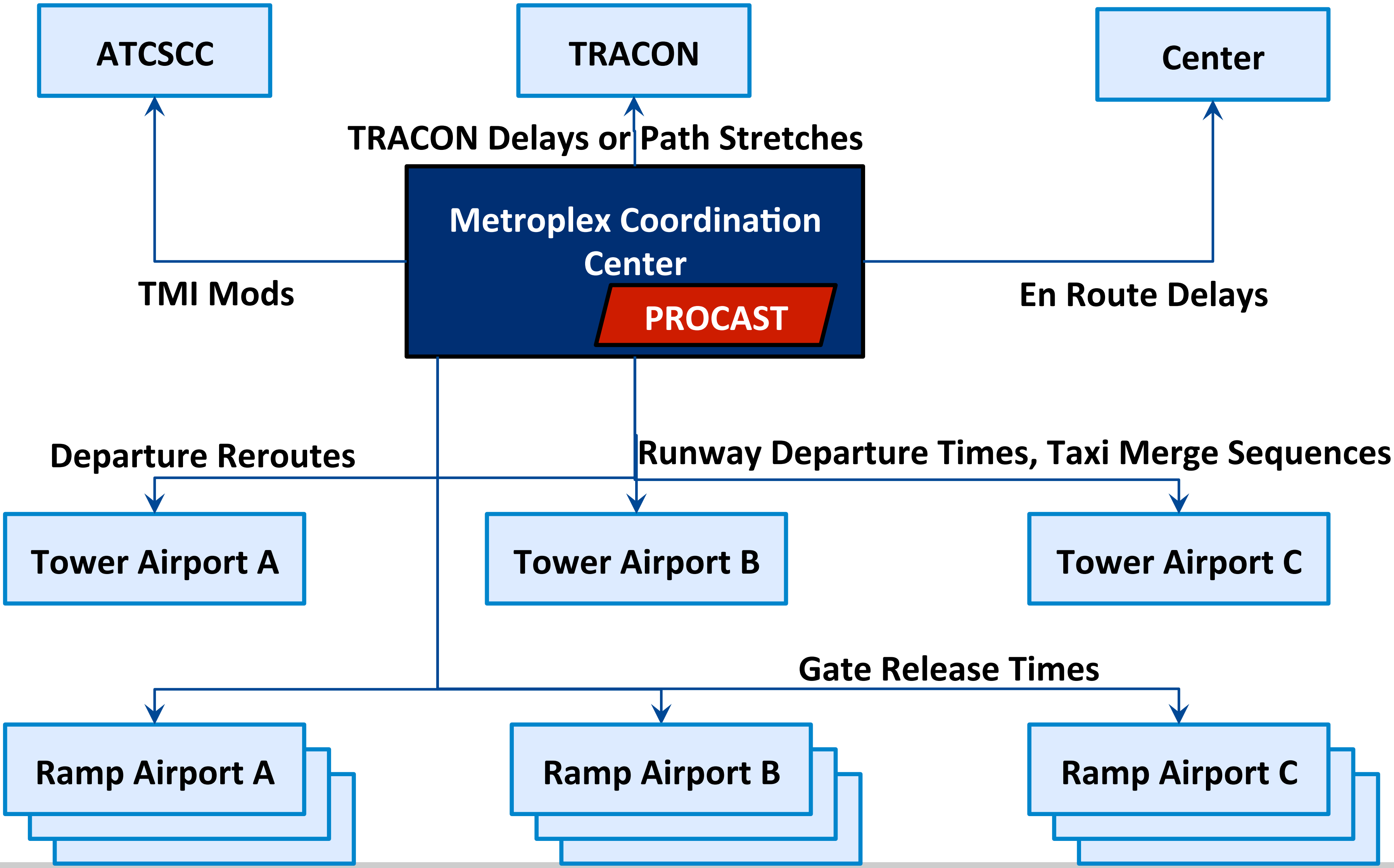
PROCAST CONCEPT OF OPERATION



SUMMARY AND KEY LESSONS LEARNED

- PROCAST showed significant benefits in proof-of-concept simulation experiments
  - 3000 hours of delays saved, $322K annual savings in fuel cost, $ 5 million savings in operating cost, $ 15 million in passenger time savings
- Predictive component by itself (BBNs-only) showed benefit
  - Speed of computation limited our ability to assess scheduling over a large number of possible futures
- Optimization-only component (NACRE-only) did not show benefit
  - Apparently sensitive to uncertainty in gate pushback readiness times

SIGNIFICANCE OF PROCAST

- Helps NASA address key aeronautics technical challenges

- Provides optimization tools and predictive capabilities that can be utilized in multiple existing NASA programs
  - Predictive and optimization support for IADS traffic scheduling algorithms
  - Coordinating surface planning with gaps in overhead en-route traffic streams
  - Predicting Traffic Management Initiatives (TMIs)
  - Evaluating candidate TMIs for Traffic Flow Management decision support

- Provides a platform for enhancing and validating NASA's airport surface simulation tool SOSS

- Applicable to any problem with three features: (i) Complex interactions/ network effects, (ii) Uncertainty, and (iii) Competing objectives
  - ATM safety assessment
  - Passenger-focused air traffic management
  - Non-ATM areas such as road transportation

NEXT STEPS

Phase I Findings	Next Steps (Phase II)
Single airport showed benefits; coordination across metroplex airports may be even more beneficial	Extend algorithms to a New York metroplex-wide scope including JFK, EWR, LGA, TEB
Current optimization capability does not fully address delay equity among airlines and airline economic objective optimization	Incorporate equity considerations and airline economic considerations (e.g., based on aircraft cost model, AOC data, number of pax, etc.)
Current optimization does not fully integrate runway sequence planning with ramp/taxiway CD&R	Enhance optimization algorithms; explore existing NASA algorithms
Computation time limited ability to assess optimization over large number of possible futures	Explore the iteration space; assess computation acceleration, e.g., leverage parallelization
Current modeling in SOSS limited to a single airport	Modeling traffic on multiple metroplex airport surfaces and in terminal airspace
Discussions with NASA IADS, ATD-2, and New York TBO research activity planners and researchers • **NASA AFH branch seminar** • **Multiple meetings throughout the year**	• **Definite interest in New York metroplex traffic management DSTs—analyze test cases** • **Enhanced SOSS will benefit IADS research** • **Potential to benefit NASA Traffic Flow Management/Machine Learning research**

PUBLICATIONS

- Papers
  - Digital Avionics Systems Conference 2014: *“Robust, Integrated Arrival-Departure-Surface Scheduling Based On Bayesian Networks”*
  - AIAA Aviation Technology Integration and Operations Conference 2015 (submitted): *“A Robust And Practical Decision Support Tool For Integrated Arrival Departure Surface Traffic Management”*

- Presentations
  - NASA AFH Branch Seminar—1/6/2015
  - Presentations to NASA SOSS simulation group—multiple
  - NASA Open House Poster presentation—October 2014
  - Presentation to FAA/JPDO representative, Sherry Boerner—July 2014
  - Presentation to NASA SARDA research group—June 2014

ACKNOWLEDGEMENTS

Thanks to…

- NARI—for the support of this project and for fostering collaboration with NASA and LEARN researchers
- Robert Windhorst, Yoon Jung—for letting us use SOSS
- Zhifan Zhu and Sergei Gridnev—for SOSS software support
- NASA SARDA, ATD-2, IADS, and New York TBO researchers—for positive feedback throughout the project
- Kristin Rozier, Johann Schumann—for pointers on Bayesian Belief Network software
- Kris Ramamoorthy and Katy Griffin (ex-Saab employees)—for your technical contributions

QUESTIONS?

(SIMULATION PLAYBACK VIDEO)

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